Journal of Electrical Engineering & Technology Vol. 4, No. 4, pp. 531~537, 2009 **531**

Simulations of Frequency-dependent Impedance of Ground Rods Considering Multi-layered Soil Structures

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Abstract – Lightning has a broad frequency spectrum from DC to a few MHz. Consequently, the high frequency performance of grounding systems for protection against lightning should be evaluated, with the distributed parameter circuit model in a uniform soil being used to simulate grounding impedances. This paper proposes a simulation method which applies the distributed parameter circuit model for the frequency-dependent impedance of vertically driven ground rods by considering multi-layered soil structures where ground rods are buried. The Matlab program was used to calculate the frequency-dependent ground impedances for two ground rods of different lengths. As a result, an increase of the length of ground rod is not always followed by a decrease of grounding impedance, at least at a high frequency. The results obtained using the newly proposed simulation method considering multi-layered soil structures are in good agreement with the measured results.

Keywords: Frequency-dependent grounding impedance, Ground rod, Distributed parameter circuit model, Multi-layered soil structure, Soil resistivity

1. Introduction

When lightning surge currents flow through a ground rod, the grounding system shows transient impedance characteristics depending on the frequency of current flowing into the grounding system. The lightning current gives a wide-band frequency spectrum ranging from DC to a few MHz. As an example, if considering a lightning current waveform with an 8/20 μs waveshape, 10% of this energy is contained in frequencies less than 2.5 kHz, while 90% of the energy is contained in frequencies less than 33 kHz [1]. The measurement of ground resistance with conventional low frequency (128 Hz) instruments might not provide data indicative of the ground response to a lightning surge. The steady-state ground resistance measured at low frequency is being used at present to determine the performance of a grounding system for protection against lightning [2]. It is necessary to evaluate the high frequency performance of a grounding system for protection against lightning since the aim of the grounding system is to provide a low impedance path to the earth for lightning currents.

Recently, different methods for analysis of the frequency-dependent transient behavior have been developed based on different approaches (for example, on circuit theory, transmission line theory, electromagnetic field theory and hybrid methods) [3-5]. The distributed parameter circuit model for simulating the frequency-dependent impedance of grounding electrode systems is based on the transmission line theory of a power system and assumes a single layer of soil with uniform resistivity [6]. Actual soil structures, however, consist of various layers with different resistivities and because of this mismatch there are significant differences between the measured results and data collected from simulation studies using the distributed parameter circuit model.

In view of this discrepancy, this paper proposes the use of a new simulation method applying the distributed parameter circuit model for frequency-dependent impedance of a ground rod considering a more detailed soil structure. In this work, the Matlab program has been used to calculate the frequency-dependent grounding impedances for two ground rods with different lengths of 10 m and 48 m. The results calculated using the newly proposed simulation method are presented and compared with the measured results and the simulated results by using the distributed parameter circuit model assuming a uniform soil structure.

2. Necessity of Consideration for Soil Structure

The role of a grounding system is to enable current of any origin to flow into the ground. This current flows into the soil in the form of leakage currents distributed along one (or more) buried ground rod(s). The distributed parameter circuit nature of the current flowing in a ground rod is then taken into account by using the transmission line theory [7]. The ground rod is divided into very small segments of length Δl. In the condition of uniform soil resistivity, the current flowing through each segment is uniformly distributed into the soil at a power frequency. However, under conditions of multi-layered soil with different resistivities, the leakage current of each segment varies with the soil resistivity of each layer as illustrated in Fig. 1.

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Received 10 April, 2009; Accepted 7 September, 2009

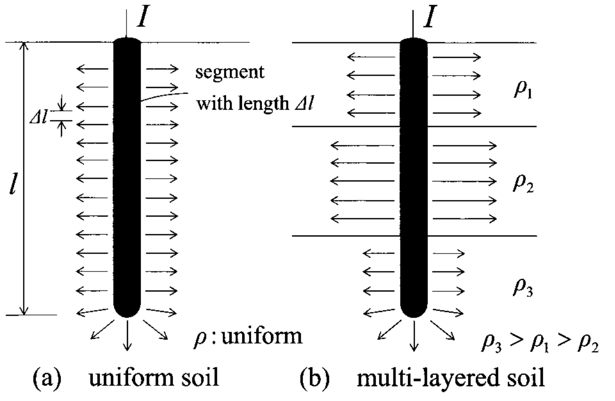


Fig. 1. Flows of power frequency current in different soil resistivity conditions

Hence, the condition of soil resistivity should be considered when designing the ground rod.

Also, at higher frequency, the variation of soil resistivity with the position of each segment influences the leakage current of each segment. Hence the different resistivities at each soil layer should be considered when designing grounding electrode systems.

3. Theory of The Distributed Parameter Circuit Model in Uniform Soil

The long ground rod is an extended grounding system where voltage and current waves are dissipated while traveling along the length of the long ground rod [8]. The long ground rod is simulated as a transmission line, as shown in Fig. 2, where L is the inductance per meter of the ground rod, C and G are its capacitance and leakage conductance per meter to ground, and the internal resistance of the ground rod is neglected.

When the ground rod is vertically buried in a uniform and isotropic soil, the ground resistance, R_0, of a driven ground rod is given by Tagg's equation as follows [9]:

$$R_0 = \frac{\rho}{2\pi l}\ln\frac{4l}{d} \quad [\Omega] \tag{1}$$

where l and d are the length and diameter of the ground rod respectively, and ρ is the soil resistivity. The ground resistance decreases as the buried length of the ground rod increases.

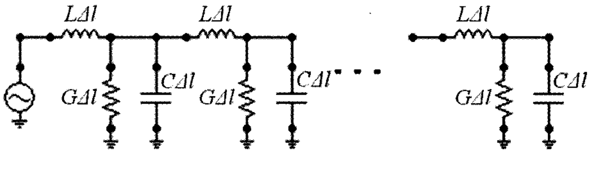


Fig. 2. Equivalent circuit of a long ground rod

The leakage conductance, G, capacitance, C per meter to ground and the inductance, L per meter of the ground rod can be calculated by dividing the lumped parameters by the length of a ground rod l:

$$G = \frac{2\pi}{\rho \ln\frac{4l}{d}} \quad [\text{mho/m}] \tag{2}$$

$$C = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\frac{4l}{d}} \quad [\text{F/m}] \tag{3}$$

$$L = \frac{\mu_0}{2\pi}\ln\frac{4l}{d} \quad [\text{H/m}] \tag{4}$$

where ε_0 and μ_0 are the permittivity and permeability of free space, respectively.

The grounding electrode system appears to the lightning impulse as a transmission line where the wave propagation theory applies, with the normal rules of reflection and group velocity [1].

For the wave propagation equations, $\boldsymbol{\alpha}$ is known as the propagation constant, and $\mathbf{Z}_c$, is called the characteristic impedance; neglecting the internal resistance of the ground rod, as can be seen in Fig. 2, both are determined using the following relations:

$$\boldsymbol{\alpha} = \sqrt{jwL(G + jwC)} \tag{5}$$

$$\mathbf{Z}_c = \sqrt{\frac{jwL}{G + jwC}} \tag{6}$$

Considering the ground rod as a transmission line open at the lower end, the grounding impedance, $\mathbf{Z}$, can be calculated as follows:

$$\mathbf{Z} = \frac{e^{2\alpha l} + 1}{e^{2\alpha l} - 1}\mathbf{Z}_c \tag{7}$$

With Eq. (7) the impedance of the ground rod can be calculated from the distributed parameter circuit model in a uniform soil [10].

4. Methodology for Simulating Grounding Impedance in Multi-layered Soil

In order to simulate a wave propagation characteristic in a ground rod buried in multi-layered soil, the existing distributed parameter circuit model needs to be modified using the wave propagation equations. Considering the ground rod as a single-phase transmission line, the wave propagation equations are given by:

$$\mathbf{E}_s = \mathbf{E}_r \cosh(\alpha l) + \mathbf{I}_r \mathbf{Z}_c \sinh(\alpha l) \tag{8}$$

$$\mathbf{I}_s = \mathbf{I}_r \cosh(\alpha l) + \frac{\mathbf{E}_r}{\mathbf{Z}_c} \sinh(\alpha l) \tag{9}$$

where $\mathbf{E}_s$ and $\mathbf{I}_s$ are the voltage and the current at the sending end, $\mathbf{E}_r$ and $\mathbf{I}_r$ are the voltage and the current at the receiving end of the ground rod, respectively.

By using the wave propagation Eqs. (8) and (9), the impedance at the sending end ($\mathbf{Z}_s$) can be derived as follows:

$$\mathbf{Z}_s = \frac{\mathbf{E}_s}{\mathbf{I}_s} = \frac{\mathbf{E}_r \cosh(\alpha l) + \mathbf{I}_r \mathbf{Z}_c \sinh(\alpha l)}{\mathbf{I}_r \cosh(\alpha l) + \frac{\mathbf{E}_r}{\mathbf{Z}_c} \sinh(\alpha l)} = \frac{\mathbf{Z}_r \cosh(\alpha l) + \mathbf{Z}_c \sinh(\alpha l)}{\cosh(\alpha l) + \frac{\mathbf{Z}_r}{\mathbf{Z}_c} \sinh(\alpha l)} \tag{10}$$

Except for the impedance at the receiving end ($\mathbf{Z}_r$), other parameters are determined by l and d, ρ, ε_0, μ_0. Therefore, if $\mathbf{Z}_r$ is known, then $\mathbf{Z}_s$ can be calculated from Eq. (10).

Fig. 3 shows a typical example of a ground rod buried in multi-layered soil where it can be seen that the upper end of the ground rod is on the right side, and its lower end is on the left side. The ground rod is considered as a transmission line whose lower end is open circuited so that in segment 3, $\mathbf{Z}_{3r}$ is considered as an infinite value ($\mathbf{Z}_{3r} = \infty$), and the $\mathbf{Z}_{3s}$ can be calculated by using Eq. (10).

In segment 2, $\mathbf{Z}_{3s}$ can be considered as the receiving end impedance of segment 2, $\mathbf{Z}_{2r}$ ($\mathbf{Z}_{2r} = \mathbf{Z}_{3s}$). As $\mathbf{Z}_{2r}$ is known, $\mathbf{Z}_{2s}$ can be calculated by using Eq. (10). In the same way, the sending end impedance of segment 1, $\mathbf{Z}_{1s}$, can be calculated. In the entire ground rod, $\mathbf{Z}_{1s}$ is the sending end impedance. Therefore, the impedance of the ground rod, $\mathbf{Z}$, is equal to $\mathbf{Z}_{1s}$:

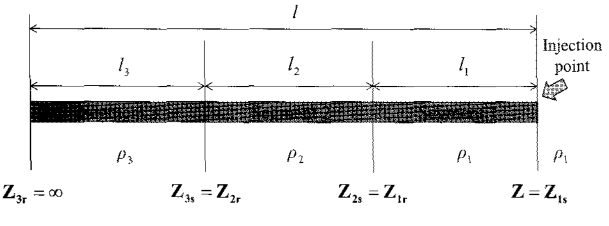


Fig. 3. Ground rod buried in multi-layered (three layers) soil

$$\mathbf{Z} = \mathbf{Z}_{1s} \tag{11}$$

5. Conditions of Ground Rods and Soil for Measurement and Simulation

In this paper, two vertically buried ground rods having the same diameter of 0.054 m and different lengths of 10 m and 48 m were investigated. In order to simulate the frequency-dependent grounding impedance for each of the two ground rods with lengths of 10 m and 48 m, the soil resistivity of the test site is measured and analyzed. This is done using the dipole-dipole method, and Fig. 4 shows the soil resistivity mapping at the test site where the ground rods are buried.

Table 1 shows the steady state ground resistance of each ground rod. The steady-state ground resistances of each ground rod are measured using the fall-of-potential method and the equivalent soil resistivity at the buried point of each ground rod is calculated from Eq. (1), known as Tagg's equation.

The soil structure is simplified to being several layers with different soil resistivity, as shown in Fig. 5. For the top layer, the soil resistivity was measured using the Wenner four electrode method because the soil resistivity mapping does not give the resistivity of the top layer of the soil, which is 1.2 m in depth.

It is impossible to measure the permittivity of each soil structure and so it was assumed that the permittivity of the soil where each ground rod is buried is uniform, and the value of the soil relative permittivity is usually assumed between 4 and 80, according to the soil humidity [11, 12].

Table 1. Ground resistance and equivalent soil resistivity.

Ground rod	Ground resistance [Ω]	Equivalent soil resistivity [Ω·m]
10 m ground rod	9.30	88.43
48 m ground rod	5.55	203.61

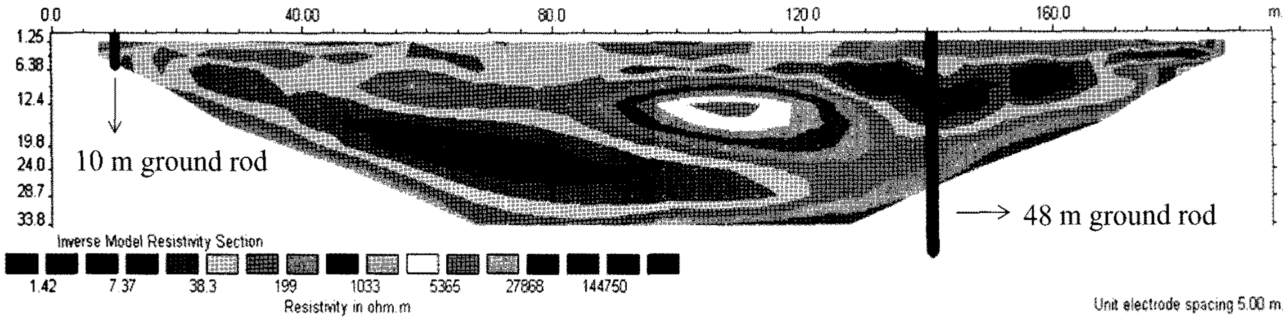
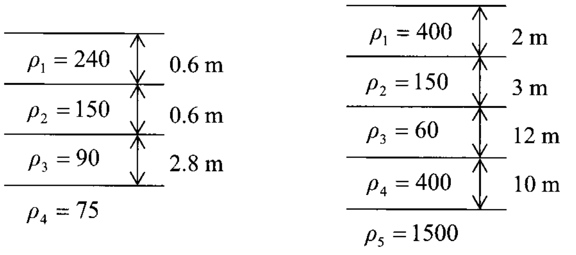


Fig. 4. Cross sectional view of soil resistivity mapping at the test site



(a) soil structure surrounding 10 m ground rod

(b) soil structure surrounding 48 m ground rod

Fig. 5. Simplified soil structure at the test site where the ground rods are buried

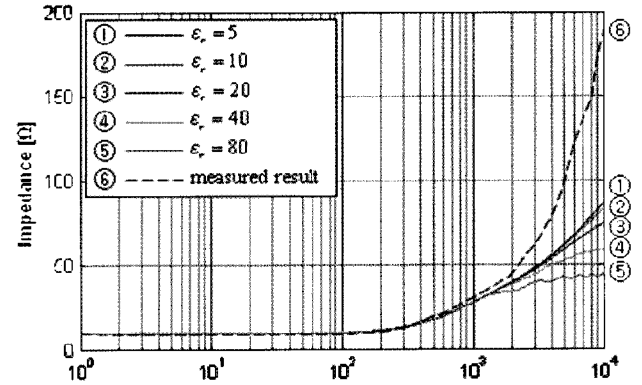
6. Results and Discussion

Investigations based on the measurements and simulations for each of two actual ground rods with lengths of 10 m and 48 m have been carried out, and the measured and simulated results are compared with each other. The revised fall-of-potential method, recommended by IEEE 81.2-1991, has been used in the measurements of grounding impedance [13]. The frequency-dependent impedances of each ground rod were measured using the method shown in [14]. The frequency was automatically increased by the measuring instrument. In the case of simulations, the distributed parameter circuit model in a uniform soil and the proposed distributed parameter circuit model in a multi-layered soil have been employed.

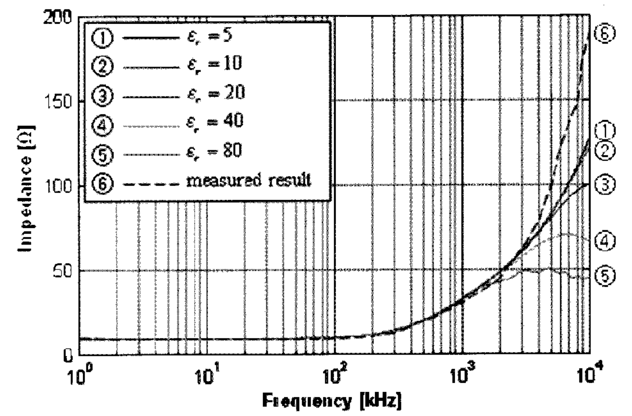
Fig. 6 shows the measured and simulated results of the grounding impedances of the 10 m long ground rod as a parameter of soil relative permittivity. The grounding impedance is determined as the ratio of the voltage developed at the feeding point to the injected current as a function of frequency. The frequency-dependent grounding impedance was analyzed using a uniform soil model and multi-layered soil model as a parameter of soil relative permittivity where the value of soil relative permittivity is assumed to be between 5 and 80.

The grounding impedance of the 10 m long ground rod is equal to the steady-state ground resistance in the frequency range of less than 100 kHz and is shown to increase from 100 kHz, and its value at 1 MHz is approximately 3 times the steady-state ground resistance. That is, the grounding impedance of the 10 m long ground rod is higher than the steady-state ground resistance, due to an inductive behavior.

The simulated results are independent of the soil relative permittivity up to the frequency of about 1 MHz and in good agreement with the measured result. Also, the simulated results over the frequency range above 1 MHz are less than the measured value. The simulated result using the multi-layered soil model when the value of soil relative permittivity is assumed as 10 is the most consistent with the measured result in the higher frequency. The newly proposed multi-layered soil model in analysis of frequency-dependent grounding impedance is more effective in higher frequency domains.



(a) Uniform soil model

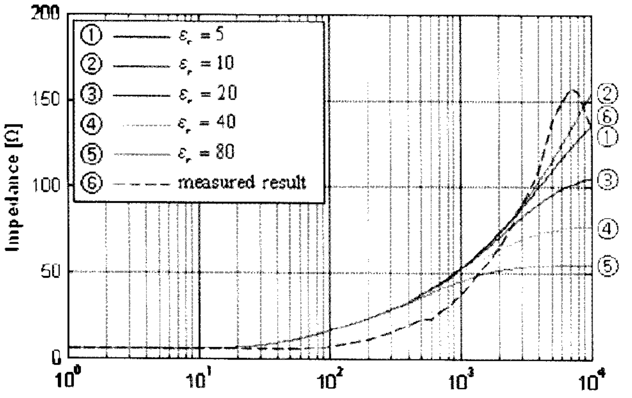


(b) Multi-layered soil model

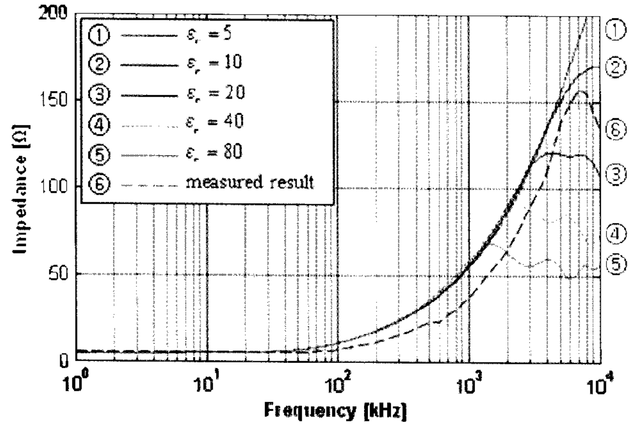
Fig. 6. Measured and simulated results of the grounding impedances for the 10 m long ground rod

Fig. 7 compares the measured grounding impedance of the 48 m long ground rod with the calculated values as a function of the soil relative permittivity. The grounding impedance of the 48 m long ground rod measured in the frequency range of less than 20 kHz was almost equal to the simulated results, but the measured result over the frequency range of a few tens kHz considerably deviated from the simulated results. The simulated values over the frequency range of a few tens kHz is greater than the measured result.

The grounding impedance of the 48 m ground rod at 1 MHz is greater than that of the 10 m ground rod, but the steady-state ground resistance measured by a conventional measuring instrument is the opposite. A low steady-state ground resistance does not always produce a low grounding impedance at high frequency since the effectiveness of grounding systems at high frequency is mostly influenced by inductive voltage drops. Longer lengths are not able to reduce the grounding impedance. Too long a ground rod is unsuitable for protection against lightning or surges. Thus, care needs to be taken when designing a grounding system for protection against lightning.

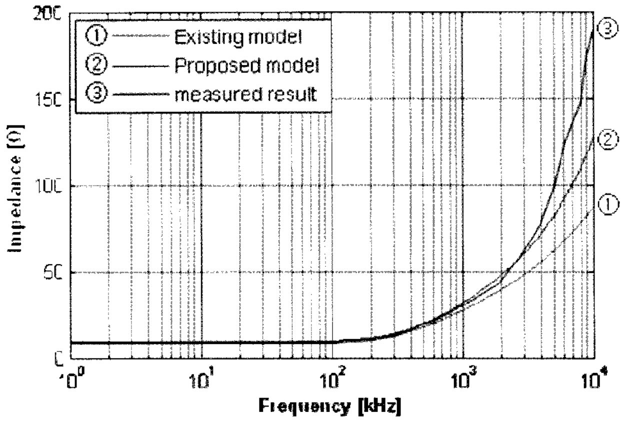


(a) Uniform soil model

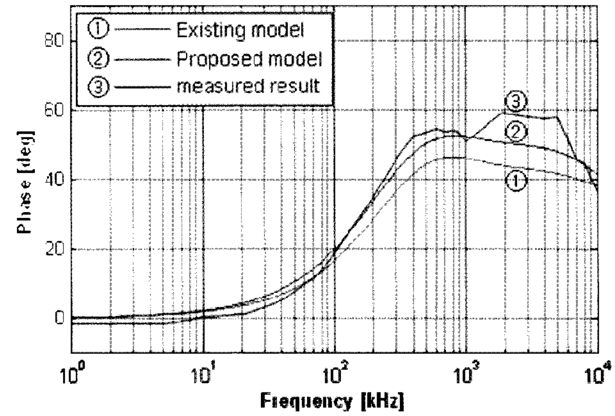


(b) Multi-layered soil model

Fig. 7. Measured and simulated results of the grounding impedances for the 48 m long ground rod



(a) Impedance



(b) Phase angle

Fig. 8. Comparison between the measured and simulated results for the 10 m long ground rod

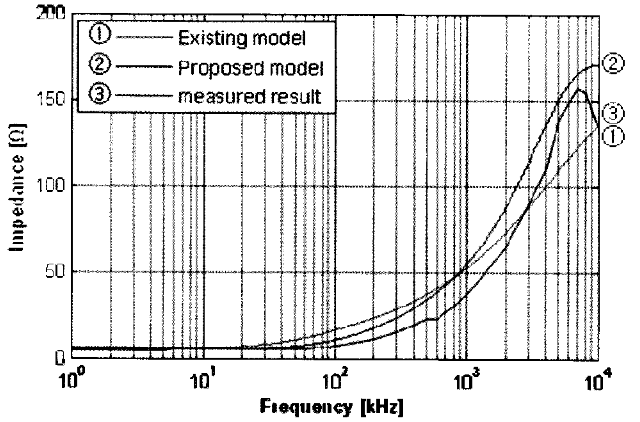
Fig. 8 shows the comparison between the results of the measurements and simulations for the 10 m long ground rod at $\varepsilon_r = 10$. It can be seen that in the frequency range from 1 kHz to 1 MHz, the agreement between the measured and simulated results of the grounding impedances is fairly good.

However, over a frequency range of more than 1 MHz, the difference between the measured and simulated impedances increases as the frequency increases. The grounding impedance simulated by the newly proposed model applying a multiple layer soil structure shows small deviations from the measured results.

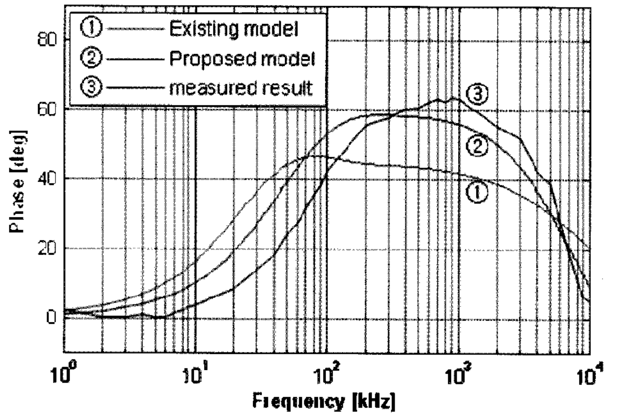
Also the measured and simulated grounding impedances are inductive for the test frequency. The phase difference for the grounding impedance simulated by considering multi-layered soil structures, as can be seen in Fig. 8(b), is closer to the measured result than the simulated result in a uniform soil structure. In the frequency range from 1 kHz to 1 MHz, the phase difference simulated by the proposed model correlates well with the measured grounding impedance, but the result of the uniform soil model shows a significant difference with the measured results. Over the frequency range of more than 1 MHz, the differences between the measured and simulated grounding impedances are relatively large. The simulated impedance phase is greater than the measured one and the deviation of the measured and simulated impedance phases is constant below a frequency of 100 kHz. The measured and newly proposed method-simulated data cross over in a frequency between 100 kHz and 200 kHz and the measured data is slightly higher the simulated data over a frequency of 200 kHz.

The comparison between the measured and simulated results for the 48 m long ground rod are shown in Fig. 9. As well as the case of the 10 m long ground rod, the magnitude and phase angle of the 48 m long ground rod impedance simulated by the newly proposed method considering multi-layered soil structures are more identical with the measured results than that by the uniform soil structure. These results show relatively large differences between the measured and simulated results in the frequency range from 1 kHz to 1 MHz, compared with the results of the 10 m long ground rod, but the results simulated by considering multi-layered soil structures are in good agreement with the measured results.

The difference between the measured and simulated impedance phases increases with the frequency from 1 kHz to 100 kHz. In the case of the 48 m ground rod, since the ground resistance is low and the inductance of the ground



(a) Impedance



(b) Phase angle

Fig. 9. Comparison between the measured and simulated results for the 48 m long ground rod

rod is high compared to the values of the 10 m ground rod, the deviation of the measured and simulated impedance phases could be increased with the frequency. It is inferred from the results of impedance phases that the inductive effect of the length of the ground rod and the grounding conductor may be worked as an overestimation for the simulations of frequency-dependent grounding impedances.

7. Conclusion

This paper has proposed a new distributed parameter circuit method of simulating the frequency-dependent impedance of ground rods considering multi-layered soil. The distributed parameter circuit model considering a uniform soil can give significant deviations from measured results in some cases. Compared with the distributed parameter circuit model in a uniform soil structure, the results achieved through simulations using the newly proposed methodology considering multi-layered soil structures are well identical with the measured results. Hence in stages of the design and simulation of a grounding system, the surrounding soil structures with different resistivities should be analyzed and considered.

Acknowledgements

This work was supported by the Ministry of Knowledge Economy under Grant R-2007-1-014.

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